Appendix B
Neptunium-237 Target Irradiation Operations in Currently Operating Reactors for Plutonium-238 Production

Neptunium-237 targets can be irradiated with neutrons to produce the plutonium-238 used in heat sources that support National Aeronautics and Space Administration (NASA) missions. The U.S. Department of Energy (DOE) has identified two of its currently operating reactors that have the potential to provide these irradiation services—the Advanced Test Reactor (ATR) at the Idaho National Engineering and Environmental Laboratory (INEEL) and the High Flux Isotope Reactor (HFIR) at the Oak Ridge Reservation (ORR). A currently operating commercial light water reactor (CLWR) of generic pressurized water reactor design has also been proposed by DOE as a possible source for the irradiation of the neptunium-237 targets. This possibility evolved as a result of DOE's request for Expressions of Interest posted in the January 4, 1999, issue of *Commerce Business Daily* (DOE 1999a).

It is anticipated that the plutonium-238 needed for the NASA missions would be produced for a period of approximately 35 years. The production of this plutonium-238 would not affect the capability of the DOE reactors to support other existing DOE missions or of the CLWR to produce commercial electricity.

Each of the reactor sites has security measures in place, including access control, and procedures to ensure the adequate protection of all materials processed and stored. Descriptions of the reactors and the plutonium-238 production processes specific to each reactor are provided in this appendix.

B.1 ADVANCED TEST REACTOR

B.1.1 Facility Description

ATR, located at INEEL, is one of the world's largest and most technologically advanced reactor test facilities. Special features of ATR include high neutron flux levels (ranging from 1×10^{15} neutrons per square centimeter per second in the flux traps to 1×10^{13} neutrons per square centimeter per second in the outer reflector positions) and the ability to vary power to fit different experiment needs in different test positions. The main purpose of ATR is to provide a prototypical reactor test environment for the study of radiation effects on materials and fuel. It is also used to produce radioisotopes for medical, industrial, and research uses. This facility description is based on information provided in the *Advanced Test Reactor Upgraded Final Safety Analysis Report* (LMIT 1997) and *Capabilities of the Test Reactor Area Featuring the Advanced Test Reactor* (DOE 1998).

ATR is located within the Test Reactor Area in the southwest portion of INEEL. The reactor, its primary coolant system, control room, and much of its auxiliary and experimental support equipment are located in Building 670. ATR began operation in 1967 and is expected to continue operating for several decades. The reactor vessel is entirely stainless steel and the core internals are replaced every 7 to 9 years, bringing the reactor to an essentially like-new condition (the most recent changeout was completed in 1994 [DOE 1998]). Buildings and structures in other parts of the Test Reactor Area provide additional support functions.

ATR is a light-water-moderated and -cooled reactor with a design thermal power of 250 megawatts. The reactor typically operates at approximately 140 megawatts or less. Typical operating cycles are 42 days or 49 days at power followed by a 7-day outage for refueling and changeout of experiments and isotope production targets. The core is 1.2 meters (4 feet) high and is surrounded by a 1.3-meter-diameter (4.25-foot-diameter) beryllium reflector. Beryllium is an excellent neutron reflector and is used to enhance the neutron flux essential to a test reactor. The location of the core in the ATR vessel is shown in **Figure B–1**. ATR has nine flux traps in its core and achieves a close integration of flux traps and fuel by means of a
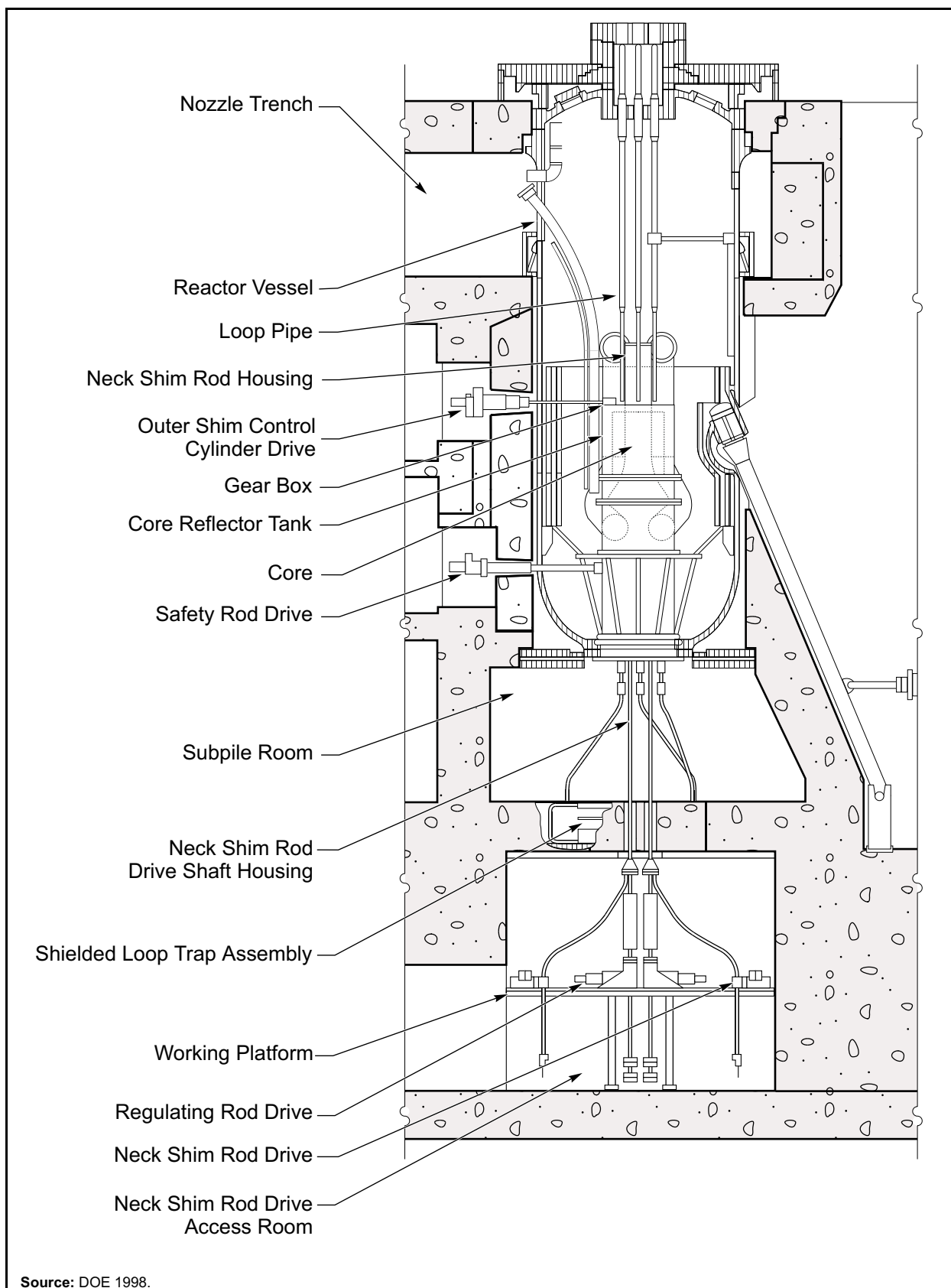
Nozzle Trench

Reactor Vessel

Loop Pipe

Neck Shim Rod Housing

Outer Shim Control Cylinder Drive

Gear Box

Core Reflector Tank

Core

Safety Rod Drive

Subpile Room

Neck Shim Rod Drive Shaft Housing

Shielded Loop Trap Assembly

Working Platform

Regulating Rod Drive

Neck Shim Rod Drive

Neck Shim Rod Drive Access Room

Source: DOE 1998.

Figure B–1 Vertical Cross Section of the ATR Vessel

serpentine fuel arrangement (**Figure B–2**). When viewed from above, the ATR fuel region resembles a four-leaf clover. The four flux traps positioned within the four lobes of the reactor core are almost entirely surrounded by fuel, as is the center position. Four other flux trap positions between the lobes of the core have fuel on three sides. The ATR's unique control device design permits large power shifts among the nine flux traps. Testing can be performed in test loops installed in some flux traps with individual flow and temperature control or in reflector irradiation positions with primary fluid as coolant. The curved fuel arrangement brings the fuel closer on all sides of the test loops than is possible in a rectangular grid.

The ATR is configured in a cloverleaf configuration. This allows for a total of nine flux traps. Of these nine flux traps, five are configured with pressurized-water loops that allow for individual temperature, pressure, flow, and chemistry controls. The five test loops are used by the Naval Reactors program. Of the remaining four flux traps, one is dedicated to the Naval Reactors program, one is used for isotope production, one is used for low-specific-activity cobalt production, and the fourth has recently had the Irradiation Test Vehicle installed. The Irradiation Test Vehicle can be described as three small pressurized-gas test loops. Use of one of these three has recently been purchased by a British corporation; negotiations for use of the other two are currently under way.

In addition to the primary flux trap irradiation positions, there are some 70 irradiation positions in the beryllium reflector (and aluminum support structure) that are available for experiment irradiation and isotope production. These position diameters range from 1.6 to 12.7 centimeters (0.625 to 5 inches) with thermal neutron flux levels ranging from 1×10^{15} to 1×10^{13} neutrons per square centimeter per second.

Approximately 25 percent of the high-flux test positions (A holes, B holes, and H holes) are currently used for iridium-192 production. The majority of the remaining high-flux test positions are used for cobalt-60 production. Occasionally, additional isotopes (e.g., strontium-89, nickel-63) are generated in small quantities. A private company leases the space for the production of these isotopes. A small number of positions are used by other companies or Government programs for other material irradiation projects. For the production of plutonium-238, neptunium-237 targets would be placed in the beryllium reflector positions. The proposed target design consists of neptunium dioxide blended with aluminum powder, pressed into a target core, and clad with aluminum. The basic ATR target should be similar in appearance to, but longer than, the typical transuranic isotope production target shown in **Figure B–3**. The ATR target length would be sized for the 1.2-meter (4-foot) active core length of ATR rather than the 0.51-meter (20-inch) active length of the HFIR target. Beryllium reflector position sizes range from 1.6 to 12.7 centimeters (0.625 to 5 inches) in diameter.

ATR is equipped with numerous safety features, including extensive plant protective systems, standby power sources, experiment interlocks, computerized surveillance, confinement systems, safety rods, and an emergency firewater injection system. ATR's six safety rods provide fast shutdown of the reactor if potentially damaging conditions develop. A sudden rise in power or coolant temperature, a sudden drop in coolant flow or pressure, or the overheating of a test sample are examples of approximately 360 conditions that would automatically drop the safety rods into the core. The firewater injection system provides emergency core cooling and flooding of the reactor vessel in the event of a loss of primary coolant.

ATR is connected by a water canal to the ATR Critical Facility. The ATR Critical Facility is a low-power, full-size nuclear duplicate of ATR, and is used to provide data, as needed, for experiment loadings prior to irradiation of the actual experiments in ATR.
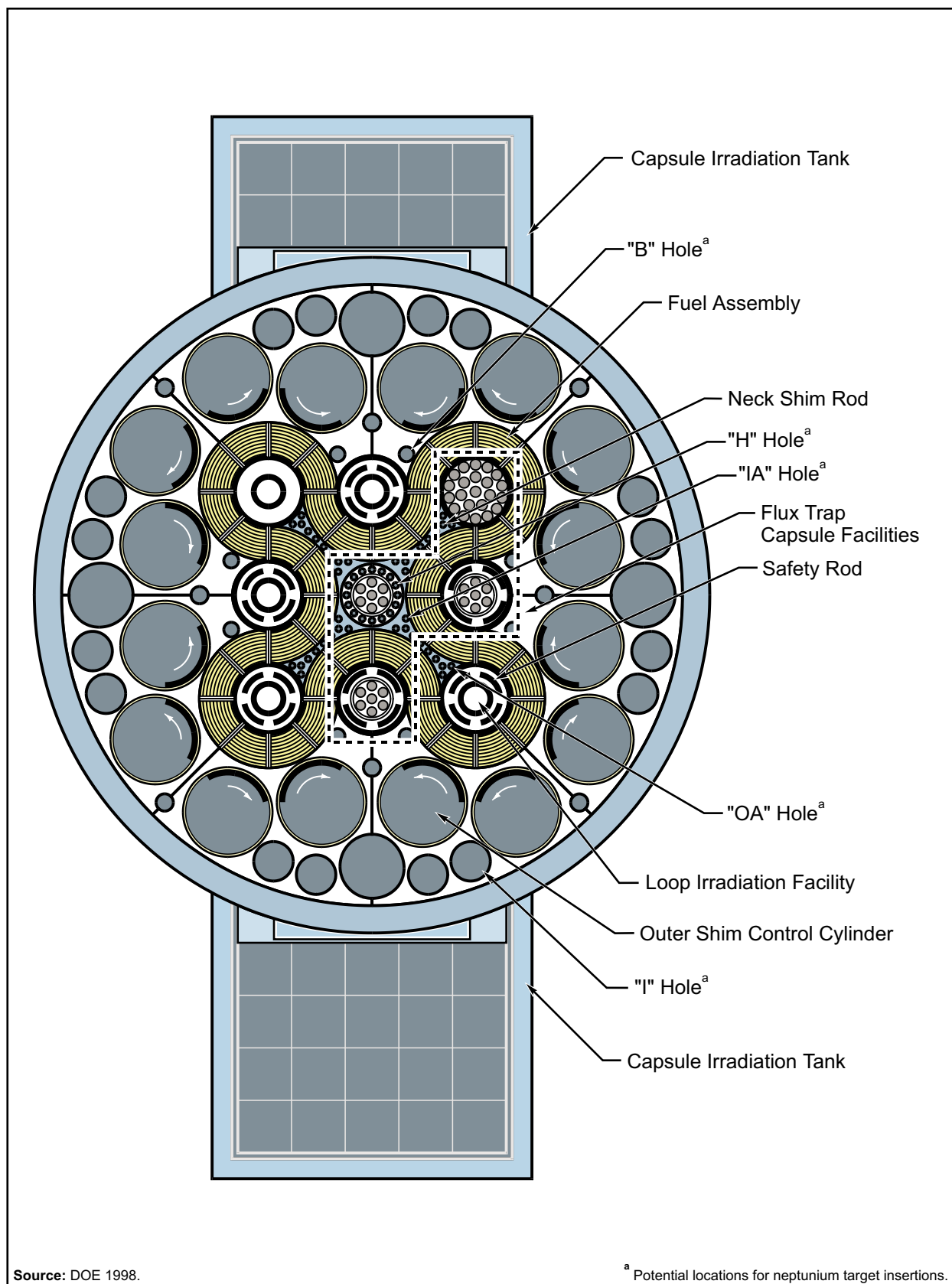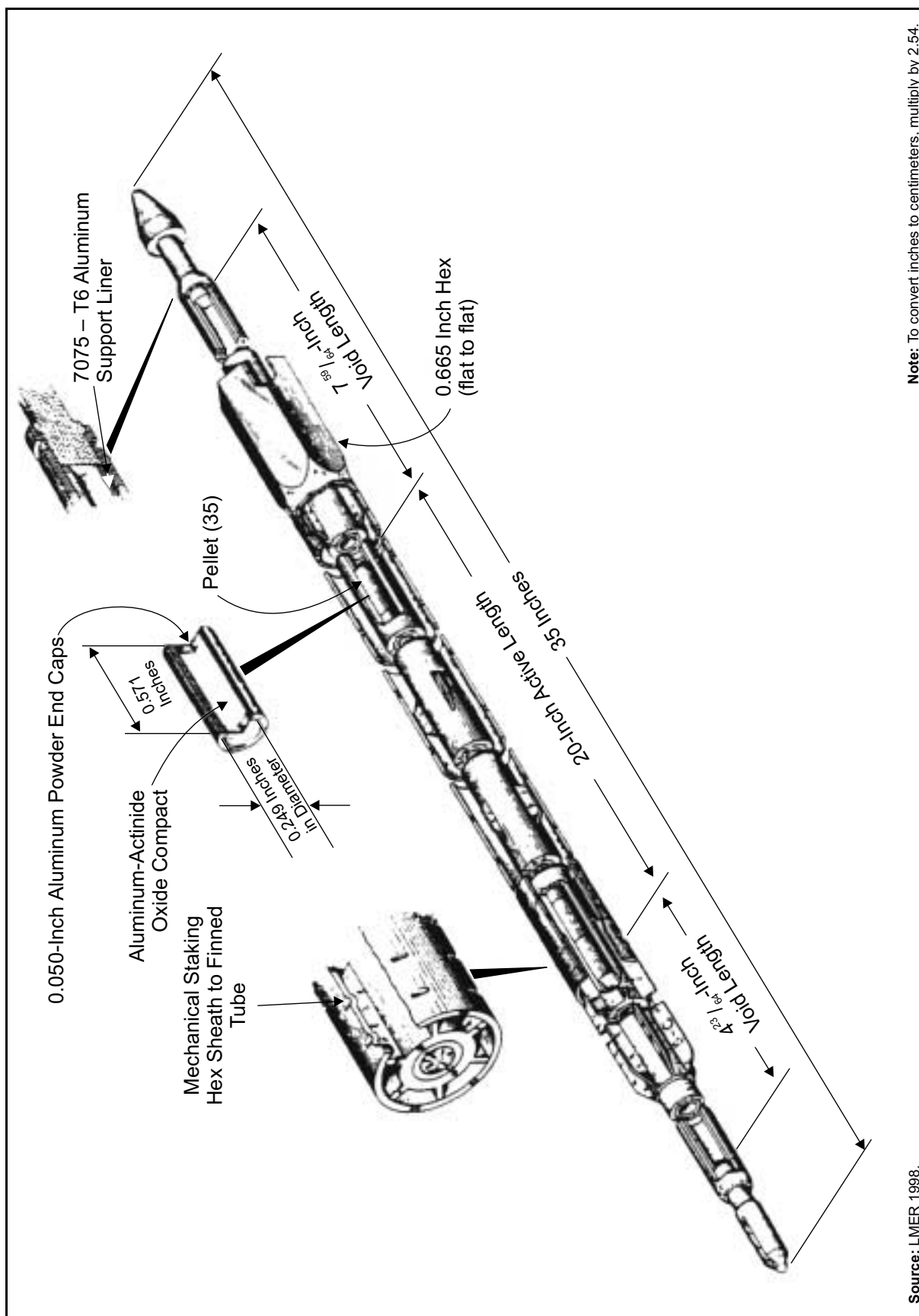
Figure B–2 ATR Core Configuration

Source: DOE 1998.

[a] Potential locations for neptunium target insertions.

Capsule Irradiation Tank
"B" Hole[a]
Fuel Assembly
Neck Shim Rod
"H" Hole[a]
"IA" Hole[a]
Flux Trap Capsule Facilities
Safety Rod
"OA" Hole[a]
Loop Irradiation Facility
Outer Shim Control Cylinder
"I" Hole[a]
Capsule Irradiation Tank

Figure B–3 Typical Transuranic Isotope Production Target

7075 – T6 Aluminum Support Liner

0.050-Inch Aluminum Powder End Caps

Aluminum-Actinide Oxide Compact

Mechanical Staking Hex Sheath to Finned Tube

Pellet (35)

0.665 Inch Hex (flat to flat)

0.571 inches

0.240 inches in Diameter

7 $\frac{59}{64}$-Inch Void Length

4 $\frac{23}{64}$-Inch Void Length

20-Inch Active Length

35 Inches

Note: To convert inches to centimeters, multiply by 2.54.

B.1.2 Process Description

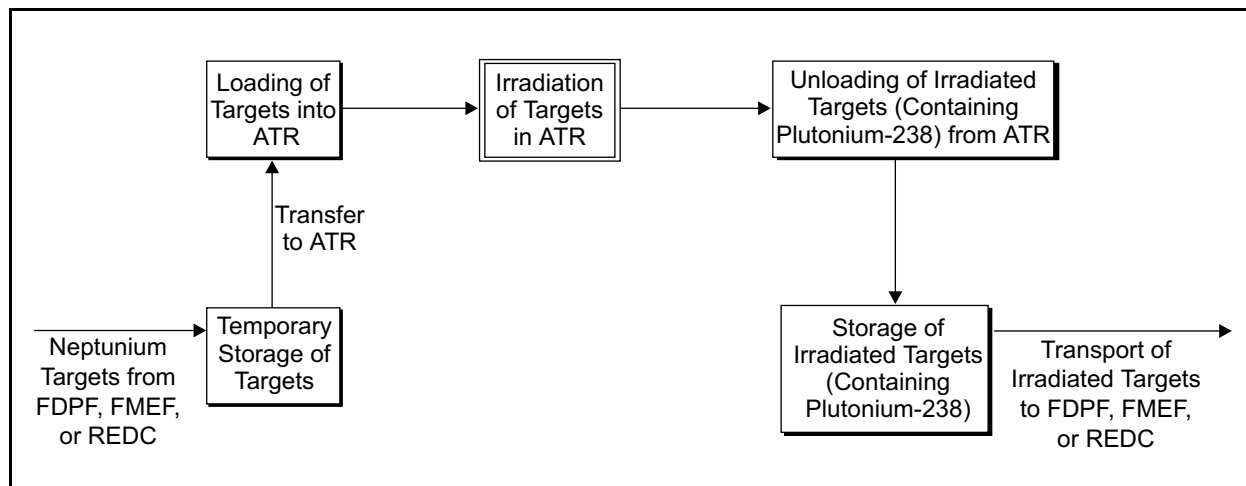The target irradiation operations using ATR at INEEL are illustrated in **Figure B–4**.

Figure B–4 Target Irradiation Operations Using ATR at INEEL

Following neptunium target fabrication at the Fluorinel Dissolution Process Facility (FDPF) at INEEL, the Fuels and Materials Examination Facility (FMEF) at Hanford, or the Radiochemical Engineering Development Center (REDC) at ORR (Appendix A), the targets would be transported to INEEL for temporary underwater storage in the ATR reactor canal pending insertion into the reactor. Each target would contain, on average, approximately 750 grams (26 ounces) (approximately 0.5 curie) of neptunium-237 and up to an equivalent amount of protactinium-233, depending on the elapsed time following the neptunium-237 purification. The targets then would be manually transferred underwater to ATR and inserted into the beryllium reflector area of the reactor. This loading would take about 2 to 4 hours to complete. Nominally, 94 targets would be irradiated concurrently in ATR for a period of about 6 months to 2 years. The length of irradiation depends on the positions of the targets in the reactor. Following irradiation, the targets, each nominally containing, on average, 63 grams (2 ounces) of plutonium-238, smaller amounts of plutonium isotopes with higher atomic weights, and larger amounts of neptunium-237 (Schnitzler 1999), would be removed from ATR using the same underwater manual transfer system used during loading and would be stored in the reactor canal. This unloading would take approximately 2 to 4 hours to complete. The irradiated targets would be stored for a period of approximately 4 to 6 months to allow for the decay of short-lived radionuclides generated during irradiation.

After storage, the irradiated targets would be transported to FDPF, FMEF, or REDC for processing to separate the plutonium-238 product. A discussion of the postirradiation activities at these facilities is provided in Appendix A.

B.2 HIGH FLUX ISOTOPE REACTOR

B.2.1 Facility Description

HFIR is located in Building 7910 of the Melton Valley 7900 Complex at ORR. REDC is also part of this complex. HFIR provides one of the highest steady-state neutron fluxes available in any of the world's reactors. The reactor is operated primarily for Neutron Science Research. It is also used to produce isotopes on a not-to-interfere basis and is the Western World's sole producer of heavy transuranium isotopes. This facility

description is based on information provided in the *HFIR Safety Analysis Report* (LMER 1998) and the *HFIR Facility Description* (ORNL 1998).

HFIR is used for the production of californium-252 and other transuranic isotopes for research, industrial, and medical applications, as well as for a variety of irradiation tests and experiments on a not-to-interfere basis with its primary mission of neutron science research. Each year, approximately 150 to 200 researchers use the experimental facilities at HFIR.

HFIR is a beryllium-reflected, light-water-moderated and -cooled reactor. Originally designed to operate at 100 million watts, the currently authorized power level is 85 million watts. The reactor core is 0.61 meter (2 feet) high, and is contained in a 2.44-meter-diameter (8-foot-diameter) pressure vessel located in a pool of water. The top of the pressure vessel is 5.18 meters (17 feet) below the pool surface, and the reactor horizontal midplane is 8.38 meters (27.5 feet) below the pool surface. The pools and experiment facilities are illustrated in **Figure B–5**.
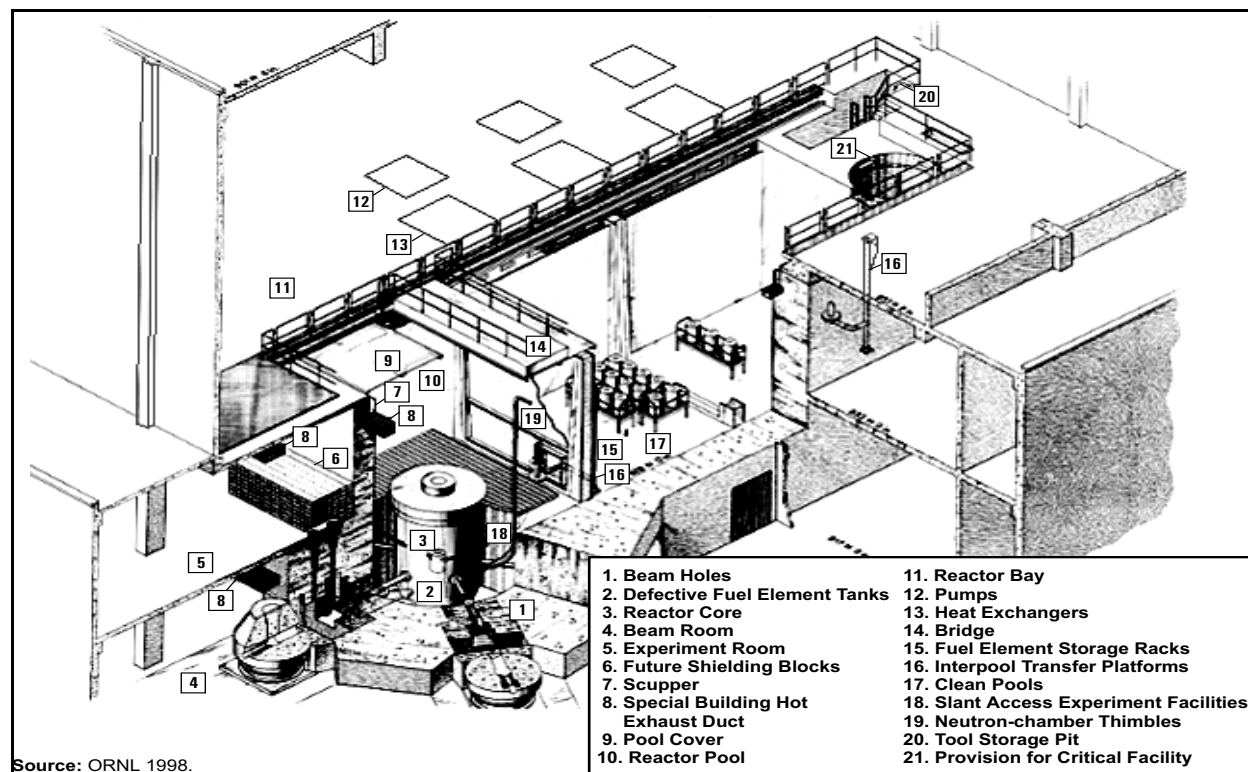

1. Beam Holes	11. Reactor Bay
2. Defective Fuel Element Tanks	12. Pumps
3. Reactor Core	13. Heat Exchangers
4. Beam Room	14. Bridge
5. Experiment Room	15. Fuel Element Storage Racks
6. Future Shielding Blocks	16. Interpool Transfer Platforms
7. Scupper	17. Clean Pools
8. Special Building Hot Exhaust Duct	18. Slant Access Experiment Facilities
9. Pool Cover	19. Neutron-chamber Thimbles
10. Reactor Pool	20. Tool Storage Pit
	21. Provision for Critical Facility

Source: ORNL 1998.

Figure B–5 Pools and Experiment Facilities

HFIR fuel contains enriched uranium-235. The reactor core consists of a series of concentric annular regions. A sectional plan view of the core is shown in **Figure B–6.** The flux trap forms a hole at the center of the core and is 12.70 centimeters (5 inches) in diameter. The fuel region surrounding the flux trap is composed of two concentric fuel elements. The inner element contains 171 fuel plates and the outer element contains 369 fuel plates. The aluminum-clad fuel plates are curved in the shape of an involute (curled spirally), thus providing a constant coolant channel width. A fuel element is illustrated in **Figure B–7**.

The fuel region is surrounded by a concentric ring of beryllium reflector approximately 0.3 meter (1 foot) thick. The beryllium is surrounded by a water reflector of effectively infinite thickness. In the axial direction, the reactor is reflected by water.
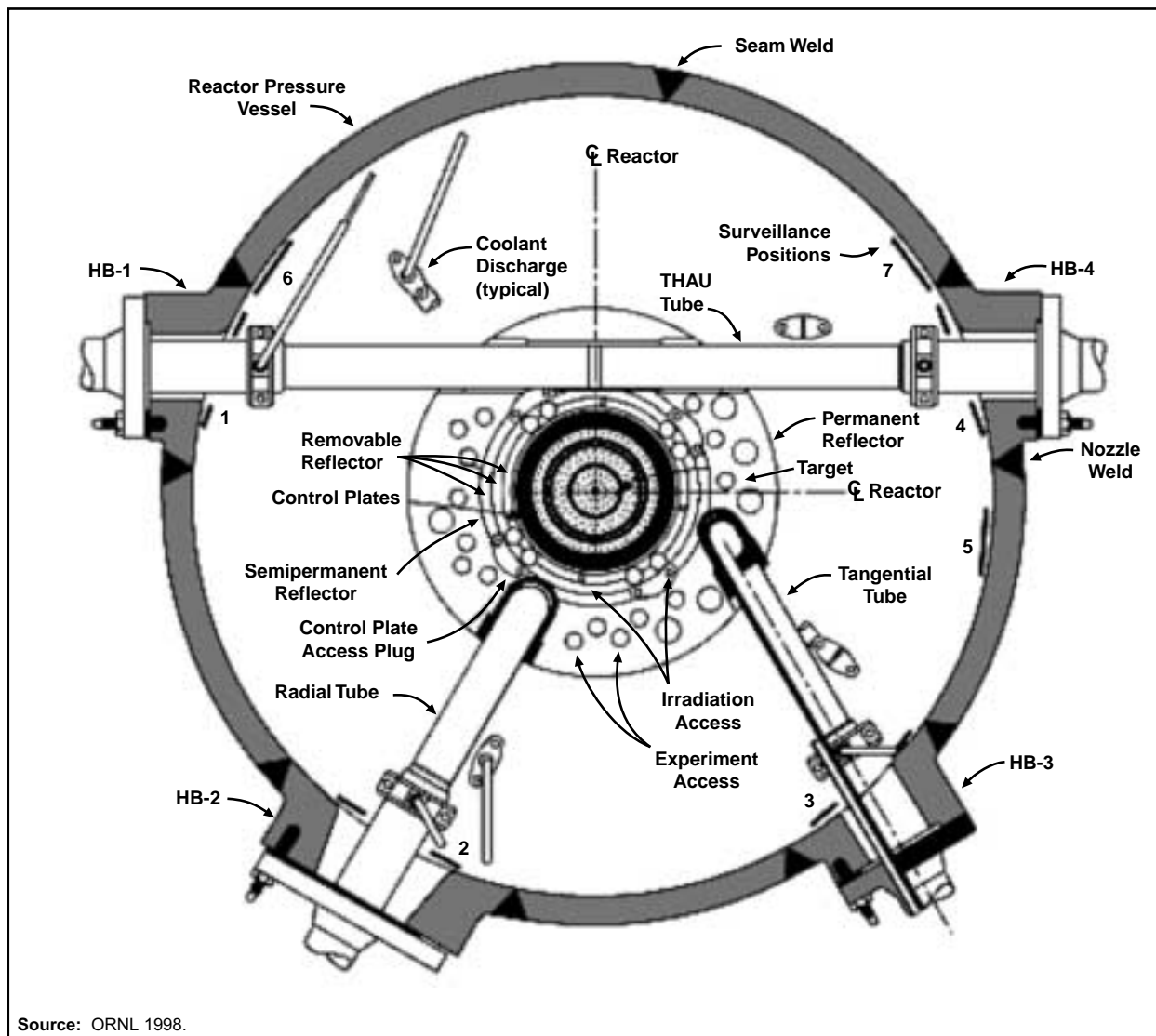
Figure B–6 Sectional View of HFIR Core

In the flux trap in the center of the HFIR fuel element, a thermal neutron flux of 2×10^{15} neutrons per square centimeter per second is available to irradiate target material. Target rods or experiments are loaded into the target holder assembly and positioned in the flux trap. There are 31 target positions in the flux trap. There are 6 peripheral target positions located at the outer edge of the flux trap, and these positions have the highest fast neutron fluxes. In addition, numerous vertical irradiation facilities of various sizes are located throughout the beryllium reflector. These are the circles of various diameters shown in the "Permanent Reflector" and "Removable Reflector" in Figure B–6. These facilities would be used for the irradiation of the neptunium-237 targets to produce the plutonium-238 addressed in this programmatic environmental impact statement if the preferred action is to use HFIR.

The control plates, in the form of two thin, boron-bearing concentric cylinders, are located in the region between the outer fuel element and the beryllium reflector. These plates are driven in opposite directions. Reactivity is increased by downward motion of the inner cylinder, which is used only for shimming (fine adjusting) and regulation; it has no fast safety function. Reactivity is increased as the outer plates are raised. Any single control element is capable of shutting the reactor down.
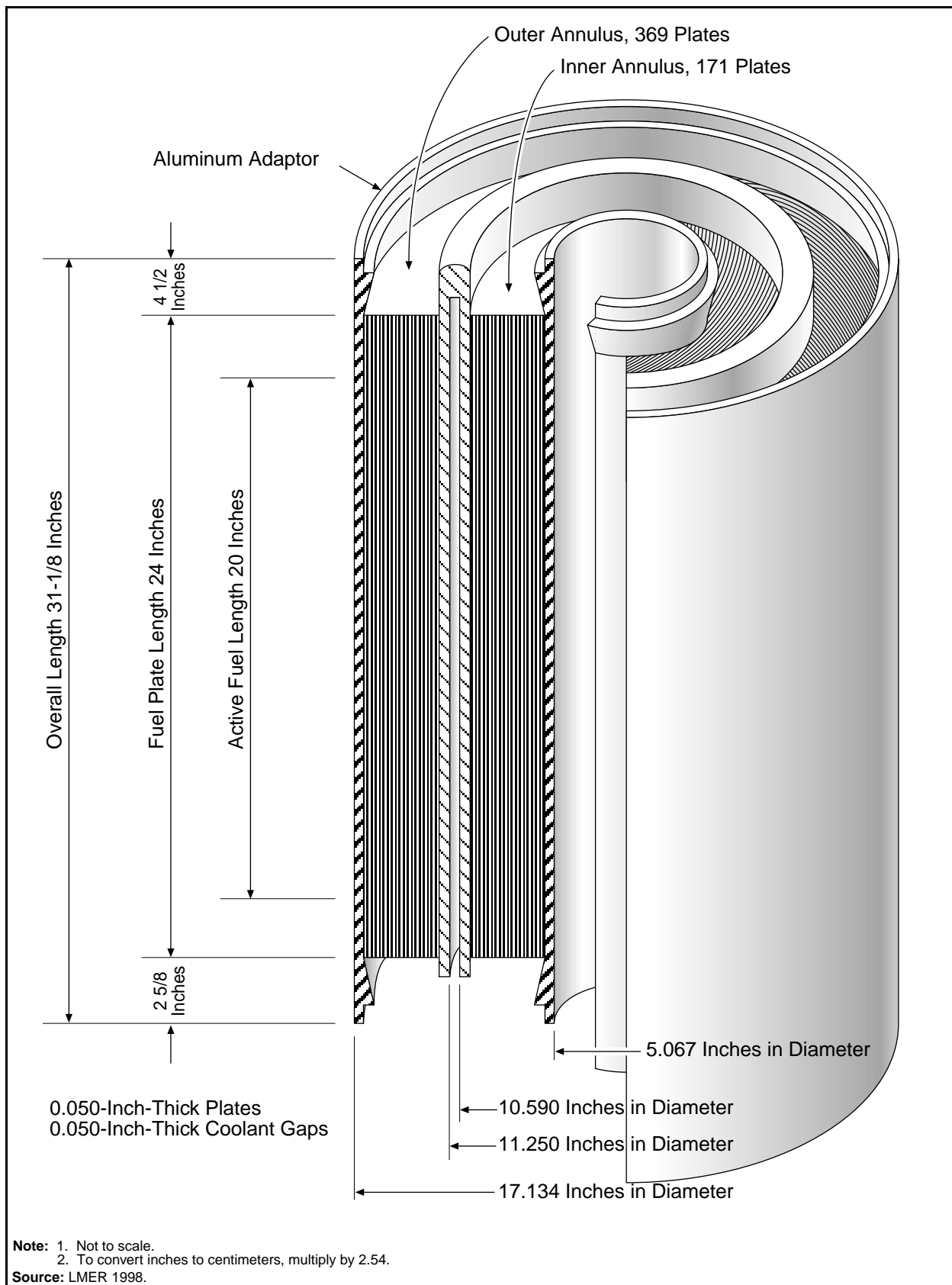
Outer Annulus, 369 Plates

Inner Annulus, 171 Plates

Aluminum Adaptor

4 1/2 Inches

Overall Length 31-1/8 Inches

Fuel Plate Length 24 Inches

Active Fuel Length 20 Inches

2 5/8 Inches

0.050-Inch-Thick Plates
0.050-Inch-Thick Coolant Gaps

5.067 Inches in Diameter

10.590 Inches in Diameter

11.250 Inches in Diameter

17.134 Inches in Diameter

Note: 1. Not to scale.
2. To convert inches to centimeters, multiply by 2.54.
Source: LMER 1998.

Figure B–7 HFIR Fuel Element

There are a variety of experimental facilities at HFIR. These are described below.

Hydraulic Tube Facility. The HFIR hydraulic tube facility consists of the necessary piping, valving, and instrumentation to move aluminum capsules containing materials to be irradiated into and from the flux trap and the capsule loading station during reactor operation. The capsule loading station is located in one of the storage pools adjacent to the pool containing the reactor vessel.

Flux Trap Target Positions. Thirty-one target positions are provided in the flux trap. These positions are usually occupied by target rods used for the production of transuranium elements; however, experiments can, in principle, be irradiated in any of these positions.

Peripheral Target Positions. Six peripheral target positions are provided for experiments located at the outer radial edge of the flux trap. Fast-neutron fluxes in these positions are the highest accessible in the reactor, although a steep radial gradient in the thermal-neutron flux exists at this location.

Large Removable Beryllium Facilities. There are eight large removable beryllium facilities. In generic terms, these are referred to as the removable beryllium positions. They are located in the removable beryllium near the control region. Either instrumented or noninstrumented experiments can be irradiated in these facilities. Instrument leads and access tubes are accommodated through penetrations in the upper shroud flange and through special penetrations in the pressure vessel upper cover. These positions can accommodate spectral-tailored (i.e., shielded) experiments, making them well suited for fusion material irradiation. When not in use, these facilities contain beryllium or aluminum plugs.

To date, these particular facilities have been used primarily for two types of irradiations: (1) high-temperature gas-cooled reactor fuel irradiations and (2) production of radioisotopes.

Small Removable Beryllium Facilities. Four small removable beryllium facilities are located in the removable beryllium near the control region. These unlined facilities have an inside diameter of 1.27 centimeters (0.5 inch). When not in use, these facilities contain beryllium plugs. These facilities have been used primarily for the production of radioisotopes.

Control Rod Access Plug Facilities. The semipermanent beryllium contains four control rod access plugs, the removal of which provides access to the coupling between the safety rods and their associated drive mechanisms. Each standard control rod access plug contains two 1.27-centimeter (0.5-inch) inside diameter unlined irradiation facilities, making a total of eight in the reactor. Normally, these facilities accommodate standard target rods of the type and configuration usually irradiated in the small removable beryllium facilities, although, in principle, experiments having other configurations can be accommodated. Only noninstrumented experiments can be irradiated in these facilities, because no provision is made for accommodating instrument leads and/or access tubes. When not in use, these facilities contain beryllium plugs.

Small Vertical Experiment Facilities. The permanent reflector is penetrated by 16 vertical holes, referred to as the small vertical experiment facilities, which extend completely through the beryllium. Each of these facilities has a permanent aluminum liner having an inside diameter of 4.01 centimeters (1.584 inches). Those located on the outer circle (five in all) are referred to as the outer small vertical experiment facilities. Vertical Experiment Facility–7 contains one of the pneumatic irradiation facilities and is unavailable for other use. Normally, noninstrumented experiments are irradiated in these facilities.

Large Vertical Experiment Facilities. The permanent reflector is penetrated by six vertical holes referred to as the large vertical experiment facilities. These facilities are similar (as to characteristics and capabilities) to the small vertical experiment facilities described in the preceding section except for location, size, and

available neutron fluxes. The aluminum liners in the large vertical experiment facilities have an inside diameter of 7.2 centimeters (2.83 inches), and the facilities are located concentric with the core on a circle of radius 46.3 centimeters (18.23 inches). When not in use, these facilities contain beryllium or aluminum plugs.

Neutron Activation Analysis Laboratory and Pneumatic Tube Facilities. Two pneumatic tube facilities are available in HFIR. These facilities are designed and built to introduce sample containers (rabbits) into the flight tubes, and irradiation stations to which the rabbits move to be irradiated. The inner diameter of the flight tubes is 15.88 millimeters (0.62 inch), and the outer diameter of the rabbit is 14.48 millimeters (0.56 inch). Capsules are inserted into the reactor and returned to shielded loading stations in the laboratory. The facilities are used to measure the trace element content in a variety of materials by neutron activation analysis. About 65 of the chemical elements can be measured in the range of 10^{-6} to 10^{-15} gram (3.5×10^{-6} to 3.5×10^{-17} ounce).

The Neutron Activation Analysis systems support Oak Ridge National Laboratory (ORNL) (DOE) programs, are used in work-for-others projects, and are available for use by students and faculty of universities through Oak Ridge Associated Universities and other programs. Several students and faculty members have used the system.

From 1975 to 1985, approximately 100,000 samples were analyzed for uranium by the delayed neutron counter in the ORR system. Most of those samples were generated by the National Uranium Resources Evaluation and the remaining ones from the Formerly Utilized Sites Remedial Action Program.

Neutron Activation Analysis at ORNL was also used to analyze evidence related to the 1961 to 1962 French-connection heroin case and the 1962 assassination of President Kennedy. More recently, it has been used in environmental analysis and in determining levels of uranium in materials used in the semiconductor industry.

Slant Engineering Facilities. Provision has been made for installation of up to four engineering facilities to provide additional neutron beams for experiments. These facilities consist of tubes that are inclined upward from horizontal. The inner ends of the tubes terminate at the outer periphery of the beryllium and have lower flux than the main beam tubes. The upper ends of the tubes terminate at the outer face of the pool wall in an experiment room one floor above the main beam room.

Gamma Irradiation Facility. Since 1968, a large variety of materials have been irradiated in the HFIR pool with the gamma flux generated from the decay of fission products in the spent HFIR fuel assemblies. In 1972, two 7.6-centimeter (3-inch) diameter stainless steel tubes were fabricated to provide a conduit through which specimens and any associated equipment could be inserted and withdrawn from the gamma fields. Facilities are also available wherein the flux trap sections of depleted fuel elements can be used to irradiate experiments requiring a high gamma flux. To date, such experiments have included studies of the effects of gamma radiation on salt, insulating materials, paint samples, and a variety of other materials.

Horizontal Beam Holes. The reactor has four horizontal beam (HB) tubes with inner diameters of 10 centimeters (3.94 inches) that extend outward from the reactor core at the midplane of the reactor. Beam tube HB–2 extends radially from the reactor centerline, and beam tube HB–3, which extends tangentially from the core, is offset 34 centimeters (13.4 inches) from the reactor center. A third tube is aligned on a tangential line 39 centimeters (15.4 inches) from the reactor centerline with both ends extending outward from the reactor to allow for the installation of two individual facilities. The tow ends of this tube are designated HB–1 and HB–4.

The average thermal flux at the end of the beam tubes for a power level of 85 megawatts is above 1×10^{15} neutrons per square centimeters per second.

Many neutron scattering facilities are found on the main experiment floor. All the neutron scattering spectrometers are located on this floor except that of the Center for Small Angle Scattering Research, which is located on the first floor above this area. The main spectrometer at each beam port uses a large monochromator shield that can be rotated under computer control to vary the orientation of the monochromator crystal.

The following paragraphs describe the instrumentation.

HB–1. The HB–1 spectrometer is generally operated as a polarized-beam spectrometer for elastic scattering studies, but it has all the capabilities of a three-axis spectrometer.

HB–1A. The HB–1A spectrometer is a recently installed triple-axis spectrometer constructed through a collaboration with Ames Laboratory at Iowa State University. The spectrometer has a fixed incident energy of 14.7 million electron volts so that high-order wavelength contamination (λn, $n = 2, 3, ...$) can be removed by a pyrolytic graphite filter. The monochromator is a double-crystal system with vertically focusing and flat pyrolytic graphite crystals. Analyzer crystals include pyrolytic graphite, germanium, or beryllium. The helium-3 detector is mounted vertically so that a large vertical divergence of the scatter beam may be used if desired.

HB–2. The HB–2 spectrometer is a very flexible three-axis spectrometer. The incident energy can be continuously varied by changing the monochromator angle. Four vertically focusing monochromator crystals are mounted on an apparatus that provides computer control of the focusing radius and of the selection of the type of crystal used in an experiment. Pyrolytic graphite, beryllium, copper, and silicon crystals are used as monochromators, depending on the desired incident energy and resolution. These same crystals are also used as analyzers. The analyzer angle is continuously variable, allowing experiments to be carried out either with fixed-incident energy or with fixed-scattered energy.

HB–3. The HB–3 spectrometer is a three-axis spectrometer that is nearly identical to the HB–2 spectrometer. The incident neutron energy is continuously variable by changing the monochromator angle, $2\Theta_M$; and four vertically focusing monochromator crystals of pyrolytic graphite, beryllium, copper, and silicon are available. A sapphire filter for the HB–3 primary reactor beam is located in the shutter, and the collimator C1 is a separate unit.

HB–3A. The HB–3A spectrometer is a small-angle scattering spectrometer that uses perfect silicon crystals to obtain high angular resolution. The angular resolution in the horizontal plane is very high, but the vertical resolution is poor; thus, the spectrometer is most useful for studies of filamentary structures. This is the structure of a fluxoid lattice aligned in the vertical direction by a magnetic field, and a number of interesting studies have been performed on superconductors using this instrument.

HB–4. The HB–4 spectrometer is a very flexible time-of-flight spectrometer. The incident neutron energy is continuously variable by changing the angle for a silicon monochromator. The silicon monochromator is also used to pulse the neutron beam by being excited with high-power ultrasonic waves. The ultrasonic frequency is high, about 10 megahertz; therefore, the time resolution is very good. Because the beam is pulsed electronically, a pulse can occur at any time, and the cross-correlation technique can be used to give a high signal-to-noise ratio. Pseudorandom pulse codes are stored in an online computer and can be of various lengths and duty cycles. The neutrons scattered from a sample are timed over a 1.5-meter (4.92-foot) flight path and can be collected simultaneously in 70 helium-3 detectors that can be placed at any position over an angular range between 10 and 130 degrees. The spectrometer can also be used as a polarized-beam time-of-flight spectrometer in which the beam polarization is varied according to a pseudorandom code. This

procedure makes the spectrometer very useful for measuring magnetic excitations in ordered ferromagnetic systems because all phonon and elastic scattering is avoided by use of the polarized beam.

A modification of the HB–4 spectrometer, which will allow it to be operated as a high-resolution powder diffractometer, was constructed recently. The new design involved the addition of a bank of 32 detectors, each with a 1.83-meter (6-foot) Soller collimator, so that a complete diffraction pattern covering a scattering-angle range of 115 degrees can be obtained by step-scanning only 3.6 degrees. Changing from the time-of-flight mode of operation to the powder-diffractometer mode is under computer control.

HB–4A. The primary spectrometer located at HB–4A is a wide-angle neutron diffractometer that is operated under a United States–Japan Cooperative Program on Neutron Scattering Research. The wide-angle neutron diffractometer uses a curved linear position-sensitive helium-3 detector that subtends a 130-degree scattering angle with a resolution of about 0.6 degree. Between the sample and the detector is a collimator, with radial cadmium-plated steel blades placed at 5-degree intervals, which oscillates back and forth during measurements to reduce background. Data are taken only when the collimator moves so that the collimator shadow is uniformly distributed over the entire detector. A beryllium monochromator provides a beam having a wavelength of 1.537 angstroms (1.537×10^{-8} centimeter) from the (101) planes. The wide-angle neutron diffractometer was designed to provide two specialized data collection capabilities: (1) time-resolved measurements of powder diffraction patterns, and (2) measurements of diffuse scattering in single crystals using the flat-cone diffraction geometry.

30-Meter Small-Angle Neutron Scattering Spectrometer. The 30-meter small-angle scattering spectrometer, constructed with funds supplied by the National Science Foundation, is also located at HB–4. This spectrometer uses pinhole geometry with collimating slits of 0.5 to 3 centimeters (0.2 to 1.18 inches) in diameter separated by a distance of 10 meters (32.8 feet). The detector, with an active area of 64 by 64 centimeters (25.2 by 25.2 inches) and resolution element dimensions of 0.5 by 0.5 centimeter (0.2 by 0.2 inch), can be positioned at any distance from 1.5 to 19 meters (4.92 to 62.32 feet) from the specimen by moving a motor-driven detector carrier along rails in the evacuated flight path. The standard incident wavelength, provided by a bank of pyrolytic graphite crystals, is 4.75 angstroms (4.75×10^{-8} centimeter). This can be changed to 2.38 angstroms by substituting graphite for the cold beryllium filter normally in position. The changeover time is less than 5 minutes, and the procedure permits experiments to be performed with increased flux over a wider range of scattering angles.

The specimen chamber is designed to accommodate standard samples, or, if necessary, it can be fitted with specialized ancillary equipment (e.g., furnaces, automatic sample changers, a Displex unit, goniometers). The monochromatic beam leaving the upper crystal bank has the approximate dimensions of the projected area of the crystals, 35 by 40 millimeters (1.4 by 1.6 inches). Three horizontal beam guide sections, each 2 meters (6.56 feet) long and with the above cross-sectional area, serve to transport the effective source to distances of 5.5, 3.5, or 1.5 meters (18.0, 11.48, or 4.92 feet) from the sample with overall gain for the appropriate experiment of a factor of about 6. The instrument is interfaced to a personal computer with a 20-megahertz, 80386 microprocessor that acts as a user interface allowing menu-driven spectrometer operations; it also permits users to transfer data on disks directly to their own laboratories after completion of an experiment.

B.2.2   Process Description

The target irradiation operations using HFIR at ORR are illustrated in **Figure B–8**.

Following neptunium-237 target fabrication at FDPF, FMEF, or REDC (Appendix A), the targets would be transported to a shielded location in Building 7930 at ORR for temporary storage. Each target would contain, on average, approximately 750 grams (26 ounces) (approximately 0.5 curie) of neptunium-237 and up to an
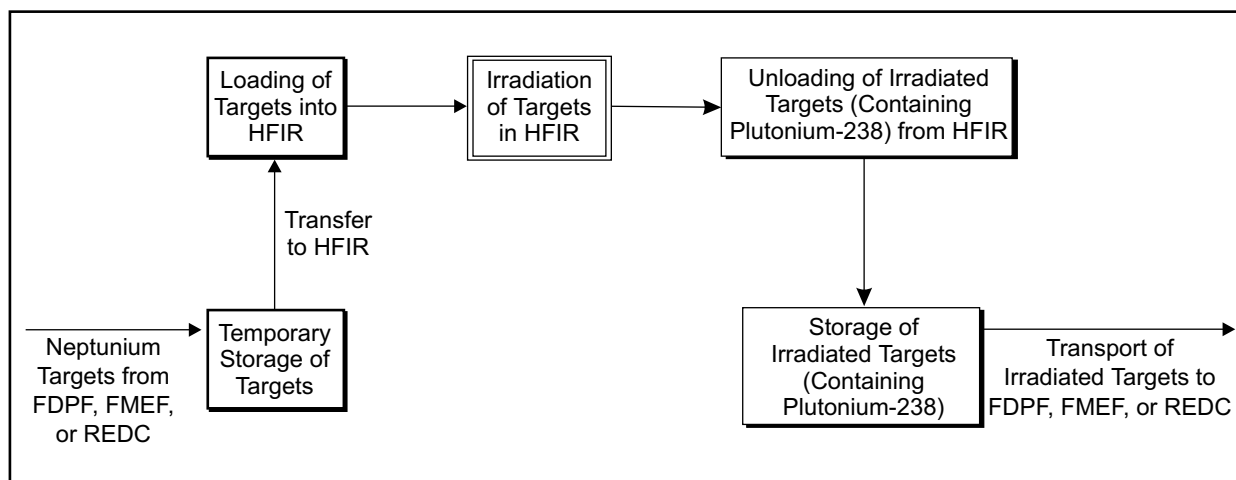
Figure B–8 Target Irradiation Operations Using HFIR at ORR

equivalent amount of protactinium-233, depending on the elapsed time following neptunium-237 purification (Wham 1999). The targets then would be transferred in transport casks to the HFIR spent fuel storage pool, where they would be stored for a period of approximately 28 to 30 days. Using a handling and underwater transfer system, the targets then would be transferred from the storage pool and inserted into the beryllium reflector (permanent or removable) area of HFIR. This loading would take approximately 2 to 4 hours to complete.

Targets would be irradiated concurrently in HFIR for a period of approximately 6 months to 2 years. The length of irradiation depends on the positions of the targets in the reactor.

Following irradiation, each target contains, on average, approximately 5 grams (0.18 ounce) of plutonium-238 along with smaller amounts of plutonium isotopes with higher atomic weights (i.e., approximately 0.65 gram [0.023 ounce] of plutonium-239 and approximately 0.06 gram [0.002 ounce] of plutonium-240) and also approximately 35 grams (1.2 ounces) of neptunium-237 (Wham 1999). The irradiated targets would be removed from HFIR using the same handling and underwater transfer system as used during loading and would be stored in the spent fuel storage pool. This unloading would take approximately 2 to 4 hours to complete. The storage of the irradiated targets would be for a period of 4 to 6 months to allow for the decay of short-lived radionuclides generated during irradiation.

After storage, the irradiated targets would be transferred to FDPF, FMEF, or REDC for processing to separate the plutonium-238 product. A discussion of the postirradiation activities at these facilities is given in Appendix A.

B.3 COMMERCIAL LIGHT WATER REACTOR

B.3.1 Facility Description

The facility description is based on information provided in the *Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor* (DOE 1999b) and in the *Final Programmatic Environmental Impact Statement for Tritium Supply and Recycling* (DOE 1995).

The generic pressurized water reactor core holds 177 fuel assemblies, as illustrated in **Figure B–9**, arranged in three regions that are rotated at about 180-day intervals (i.e., the inner region is removed as spent nuclear fuel to the cooling pond, the other two regions are moved inward, and fresh fuel is loaded into the outer
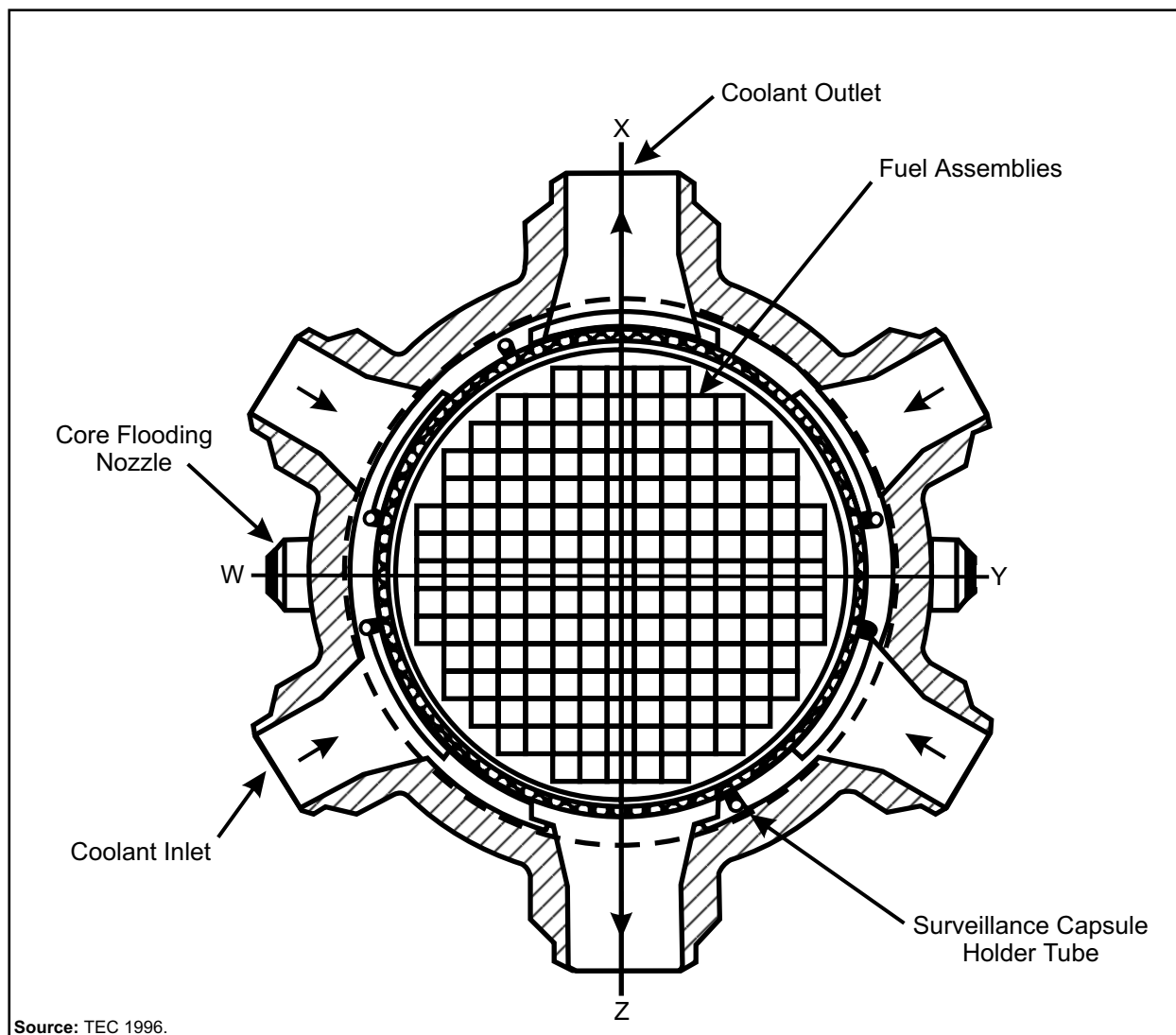
Figure B–9 Plan View (Cross Section) of a Generic CLWR

region). The fuel assemblies each utilize a 15-by-15 lattice of fuel rods consisting of slightly enriched uranium dioxide pellets clad and sealed in Zircaloy tubing. All fuel assemblies (**Figure B–10**) are identical in mechanical construction and are interchangeable in any core location. The basic fuel assembly is normally composed of 208 fuel rods, 16 control rod guide tubes, and one centrally located position for instrumentation, all within the 15-by-15 lattice. The fuel assembly is approximately 20 centimeters by 20 centimeters (8 inches by 8 inches) in cross section, with an overall length of 420 centimeters (165 inches).

In addition to the nuclear reactor and its surrounding reactor vessel, a nuclear steam supply system contains equipment and components to remove the heat of fission and to convert it into steam to drive a turbine (in test or isotope production reactors such as ATR and HFIR, the heat arising from nuclear fission is merely passed from primary to secondary coolant systems for rejection to the atmosphere through cooling towers). A schematic drawing of a pressurized water reactor nuclear steam supply system is shown in **Figure B–11**. A pressurizer keeps the water reactor coolant under sufficient pressure to prevent it from boiling. The pressurized water (primary coolant) is pumped by the primary coolant pumps to the reactor, where it is heated by the fissioning of uranium fuel taking place within the core. The secondary coolant pumps send the heated coolant to the tube-side of the steam generators, where heat is transferred to the shell-side, boiling off secondary
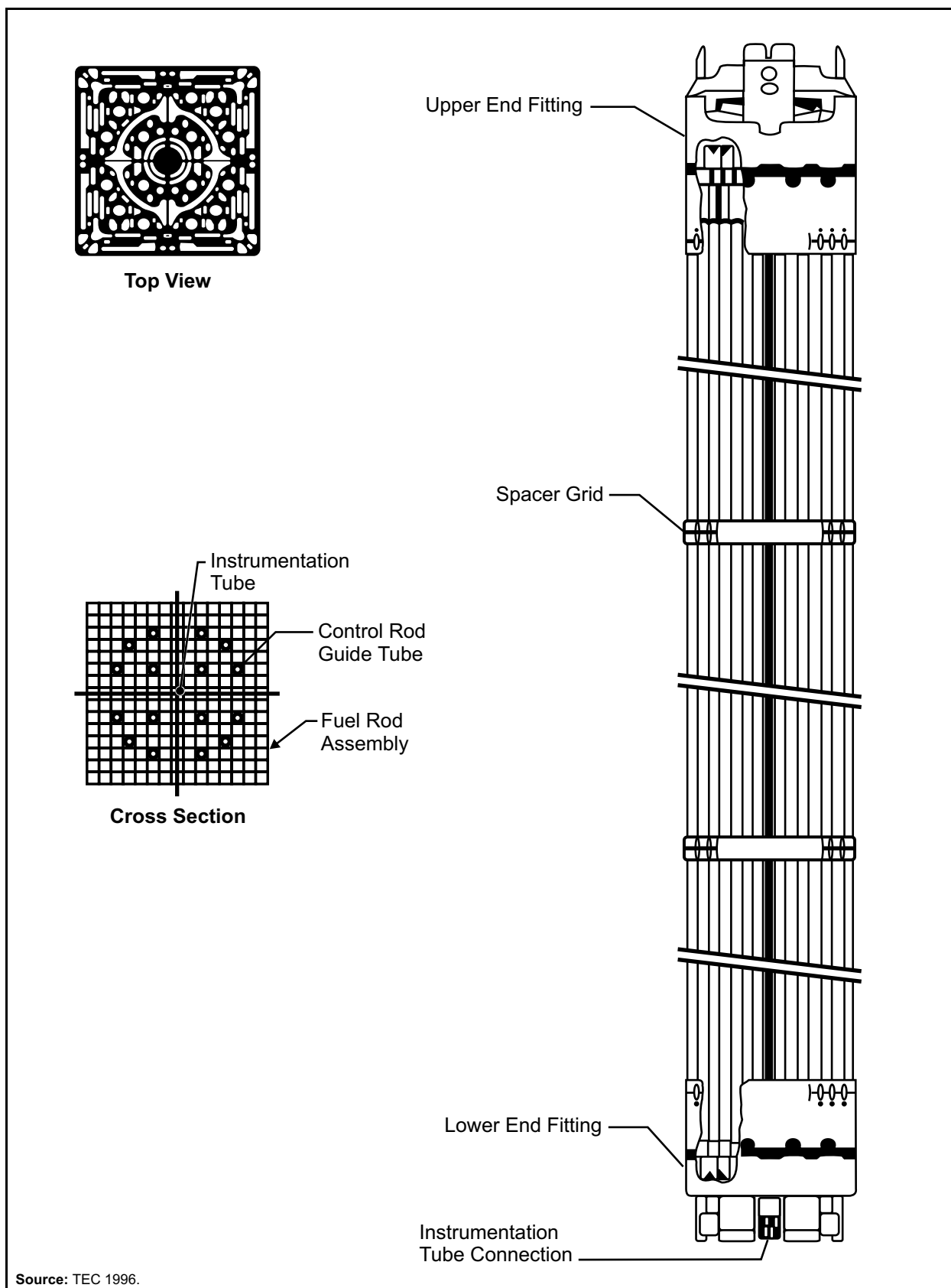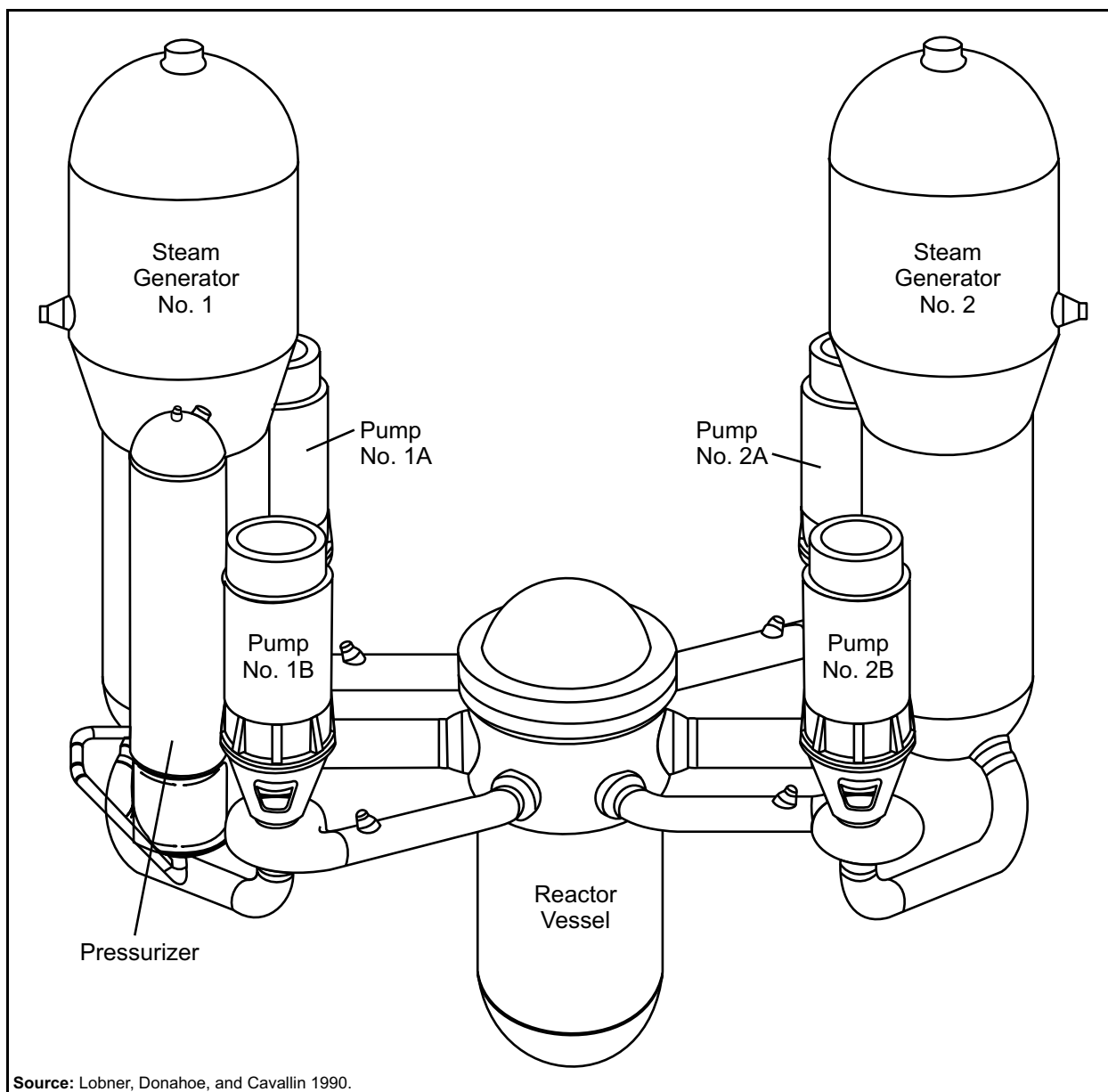
Top View

Instrumentation Tube

Control Rod Guide Tube

Fuel Rod Assembly

Cross Section

Upper End Fitting

Spacer Grid

Lower End Fitting

Instrumentation Tube Connection

Source: TEC 1996.

Figure B–10 CLWR Basic Fuel Assembly

Source: Lobner, Donahoe, and Cavallin 1990.

**Figure B–11 Schematic of a Typical Pressurized Water Reactor's
Nuclear Safety Steam Supply System**

coolant as steam to drive turbine generators. The turbine generators are outside of the nuclear steam supply system and are major components of the "balance-of-plant" systems. Exhaust steam from the turbines is condensed to lower the back-pressure on the turbines and provide heat recovery.

The particular nuclear steam supply system illustrated in Figure B–11 is arranged as two heat transport loops, each with two primary coolant circulating pumps and one steam generator. In addition to serving as a heat transport medium, the primary coolant also serves as a neutron moderator and reflector, and as a solvent for soluble boron utilized in chemical "shim" control (fine adjustment of the "reactivity," or power level of the reactor). A domed steel containment vessel envelops many nuclear steam supply system components in addition to the reactor vessel. These include the reactor coolant piping, the pressurizer, the pressurizer quench tank and coolers, reactor primary coolant pumps, steam generators, core flooding tanks, and letdown coolers.

Safety systems directly associated with this vessel include the containment spray system, the containment air cooling system, and the containment isolation system.

A second level of containment exists as the reinforced concrete shield building, which surrounds the containment vessel. It is designed to provide biological shielding during normal operation and hypothetical accident conditions. The building provides for the collection and filtration of fission product leakage from the containment vessel following a hypothetical accident by means of its emergency ventilation system. In addition, the building provides environmental protection for the containment vessel from adverse atmospheric conditions and external missiles.

B.3.2   Process Description

The target irradiation operations using a generic CLWR are illustrated in **Figure B–12**.
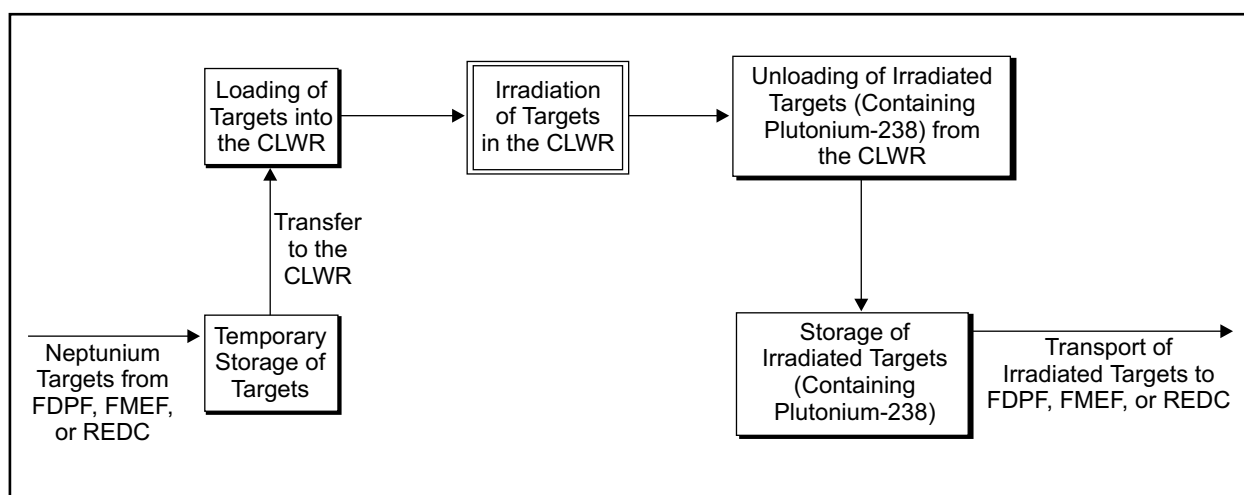

Figure B–12 Target Irradiation Operations Using a CLWR at a Generic Site

Following neptunium-237 target fabrication at FDPF, FMEF, or REDC (Appendix A), the targets would be transported to the spent fuel pool at the generic CLWR site for temporary storage. Because design of the neptunium-237 targets for the CLWR is still in the conceptual stage, the amount of neptunium-237 in each target has not yet been determined. During the period of reactor refueling, the neptunium-237 targets would be placed in a fuel assembly that was in the reactor core during the previous operating cycle. The targets would replace fuel rod positions in the fuel assembly. The removal of fuel rods from an irradiated fuel assembly and the substitution of neptunium-237 targets in the fuel rod positions would be performed in the spent fuel pool under approximately 6.1 meters (20 feet) of water to limit radiation doses to the involved workers. The Zircaloy-clad target dimensions are similar to a fuel rod, approximately 1 centimeter (0.4 inch) in diameter by 3.7 meters (12 feet) long. **Figure B–13** presents a cross-sectional view of the CLWR neptunium-237 target. The fuel assembly containing the neptunium-237 targets would be transferred from the spent fuel pool to the reactor using the refueling canal and placed in the center fuel assembly position in the reactor core (refer to Figure B–9). The neptunium-237 targets would remain in the reactor core for a complete operating cycle, nominally 18 months.

The substitution of neptunium-237 target rods for fuel rod positions in the center fuel assembly would have a minimal impact on reactor operations. The fuel rods located in the center fuel assembly position do not normally contain fresh fuel (i.e., fuel placed in the core for utilization during the first 18-month operating cycle of the reactor), but contain fuel that is in the second or third operating cycle. The normal power distribution
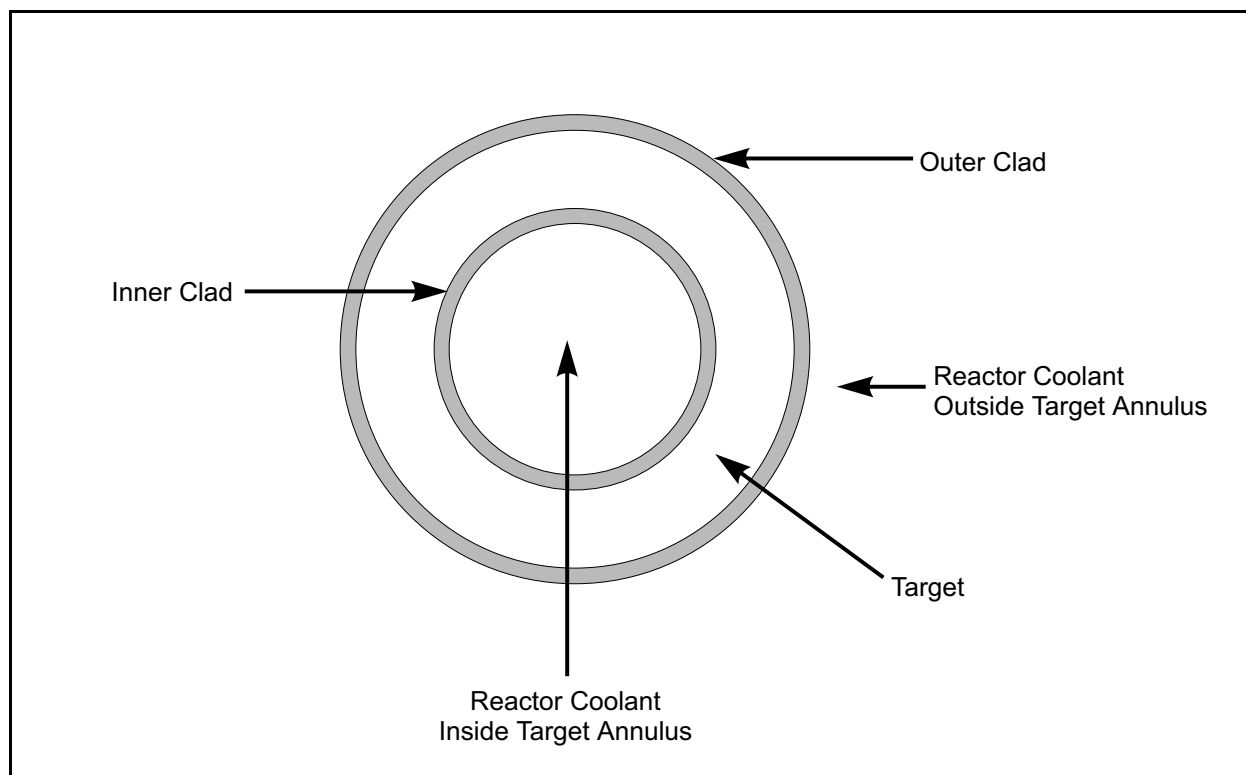
Figure B–13 Radial View (Cross Section) of a CLWR Neptunium-237 Target

within the core and reactor coolant flow and its distribution within the core would remain within existing technical specification limits.

Following irradiation for a complete operating cycle, the targets would be removed from the reactor using the same transfer system used during loading and would be stored in the spent fuel pool. The irradiated targets would be stored for a period of approximately 4 to 6 months to allow for the decay of short-lived radionuclides generated during irradiation.

After storage, the irradiated targets would be loaded in a spent fuel cask and transported from the reactor site to FDPF, FMEF, or REDC for processing to separate the plutonium-238 product and to recycle the remaining neptunium-237 for fabrication of new targets. A discussion of the postirradiation activities at these facilities is provided in Appendix A.

B.4 REFERENCES

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